European Journal of Sustainable Development (2023), **12**, 4, 225-236 ISSN: 2239-5938
Doi: 10.14207/ejsd.2023.v12n4p225

Effect of Climate Change in Years 2006-2019 on Crop Yields in Poland

By Elżbieta Wójcik-Gront[1] and Dariusz Gozdowski[1]

Abstract
In recent years, especially since 2005, a substantial increase in temperature has been observed worldwide, including in Poland. Crop production is very important for livestock feeding and food production. In this study, the effect of climate change from 2014 to 2022 on selected crops, especially winter rye yield, was evaluated. The data for the analyses were obtained from the FAOSTAT database and post-registration cultivar trials. The effect of climate change was evaluated for cereals, potatoes, and sugar beets. The trends of crop yields were evaluated using analysis of regression. The results of the study proved a positive correlation between precipitation and crop yield and a negative correlation between temperature and crop yield. The most significant effect of weather conditions was observed in the April-June period.

Keywords: climate change, rye yield, forecast.

1. Introduction

Climate change is undoubtedly one of the most important factors affecting agricultural production in the world, including Europe and Poland. In Poland, by 2100, a temperature increase of about 3-3.5°C is projected compared to the average from the second half of the 20th century (Kundzewicz and Matczak 2012). Depending on the climate scenario, this increase in temperature could be even greater, resulting in very large changes in agriculture. Climate change in Poland is mainly characterized by an increase in temperature, but an increase in precipitation variability is also observed. Annual precipitation in Poland is already slightly increasing. Precipitation forecasts for the future indicate an increase in precipitation during the winter and a decrease in the summer (Szwed 2019). Such a change in the distribution of precipitation will have a negative effect on crop yield because the shortage of water during the vegetation period will affect plant growth and development. The climate change effect on various crop species will vary depending on the climatic requirements of the crops. Probably a positive effect will be observed for crops such as soybean and maize and a negative one for such crops as winter rye or triticale. Over the last few decades, a systematic strong increase in yields of most agricultural crops in Europe, including Poland, has been observed (Peltonen-Sainio, etc. 2009; Królczyk, etc. 2014). This is mainly due to genetic progress, intensification of production, increased fertilization, and more effective plant protection. Therefore, it is difficult to unequivocally assess what effect climate change has on crop yields and what is caused by other factors. Long-term assessment of the impact of various factors over several decades is difficult due to the

[1]Department of Biometry, Institute of Agriculture, Warsaw University of Life Sciences-SGGW, Nowoursynowska 159, 02-776, Warsaw, Poland.
*Corresponding Author.

simultaneous impact of many factors and the interaction between them. Therefore, in this study, we focused on a shorter period of time to reduce the impact of other factors and at the same time try to determine the impact of climate change, which has been taking place particularly dynamically in the last dozen years (Pińskwar, etc. 2020, Ziernicka-Wojtaszek, 2021). The results presented in this article concern the research on the impact of weather conditions on various crop species throughout Poland and the study of one cultivar of winter rye (cv. Antonińskie) cultivated in a very similar crop management system in selected locations in Poland. This cultivar was chosen because rye cultivars are often cultivated for a very long period of time, while other crop cultivars, such as wheat, change as they are replaced by new cultivars.

Winter rye is a cereal grain crop that is widely cultivated in many parts of the world, including Europe, North America, and Asia (Bushuk 2001). It is a hardy crop that can tolerate cold temperatures and poor soil conditions, making it well-suited for cultivation in regions with harsh winters and short growing seasons (Blecharczyk, etc. 2016). Winter rye is primarily grown for its grain, which is used for a variety of purposes, including flour production, animal feed, and as a cover crop to improve soil health. It is also used for ethanol production and as a source of biomass for energy production. Winter rye has several advantages over other cereal crops, such as wheat and barley. It is more drought-tolerant and has better weed suppression capabilities, which can reduce the need for herbicides. It also has a deeper root system, which allows it to access nutrients from deeper soil layers, making it more efficient in its use of fertilizers. Winter rye is typically sown in the fall and harvested the following summer. It is often used as a cover crop in between cash crops, as it can help prevent erosion and improve soil health (Chmielewski and Köhn 2000, Herbstritt, etc. 2022). It can also be used as a forage crop for livestock, providing valuable grazing and hay forage (Shao, etc. 2015).

Climate change can have a significant impact on the yield of winter rye, as it can affect the temperature, precipitation patterns, and other environmental factors that influence crop growth and development. Studies have shown that warmer temperatures can have both positive and negative effects on winter rye yields, depending on the specific conditions (Hadasch, etc. 2020). For example, a study conducted in Germany found that warmer temperatures during the growing season led to increased yields of winter rye, due to a longer growing season and improved photosynthesis. However, other studies have suggested that higher temperatures can also increase the risk of drought and heat stress, which can reduce yields. Changes in precipitation patterns can also affect winter rye yields, as the crop requires adequate moisture for growth and development. Drought conditions can lead to reduced yields, while excessive rainfall can increase the risk of disease and lodging (Wójcik-Gront 2018). In addition to temperature and precipitation, other environmental factors such as soil fertility, pest and disease pressure, and management practices can also influence winter rye yields under climate change conditions. For example, increased atmospheric CO_2 concentrations may have a fertilization effect, leading to increased yields under certain conditions (Yin, etc. 2004). Overall, the impact of climate change on winter rye yields is complex and multifaceted and depends on a variety of factors. Further research is needed to better understand the specific effects of climate change on winter rye production and to develop strategies to mitigate these effects and promote sustainable crop production in a changing climate.

In recent years, especially since 2005, a substantial increase in temperature is observed worldwide, including in Poland. Crop production is very important for livestock feeding and for food production. In this study, the effect of climate change from 2006 to 2019 on selected crop yield was evaluated for the whole of Poland. Furthermore, more detailed statistical analyses were performed to evaluate the relationship between grain yield of winter rye cv. Antonińskie and weather conditions. The data for the analyses were obtained from post-registration cultivar trials. The effect of climate change was evaluated depending on various soil types with different fertility. The trends of crop yields were evaluated using analysis of regression. The results for the analyzed period were presented and scenarios for the future were prepared.

2. Materials and Methods

The first part of the study was performed for the entire country (Poland) and it was based on FAOSTAT crop yield data and weather data for the period 2006-2019. The following crops were included in the analysis: barley, maize, oats, potatoes, rye, sugar beet, and wheat. The yields of these crops for the study period are presented in Figure 1.

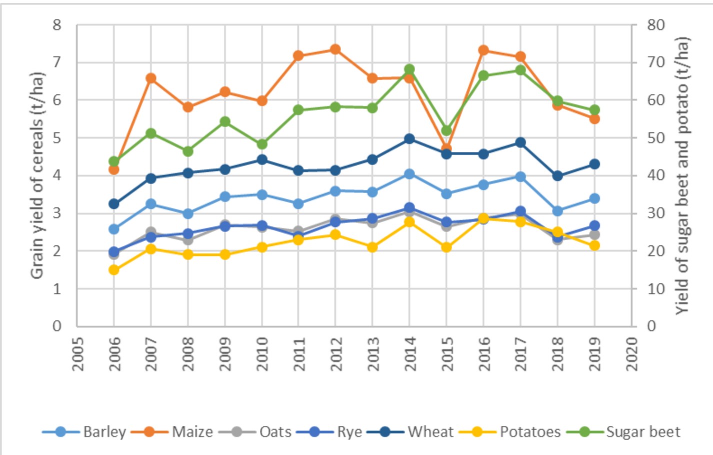

Figure 1. Mean crop yield of selected crops between 2006 and 2019 in Poland (source of data: FAOSTAT).

Meteorological data for the analyses were obtained from the Institute of Meteorology and Water Management (https://danepubliczne.imgw.pl/) for selected meteorological stations, excluding mountain stations because the cultivation of crops in these areas is very limited because of severe weather and soil conditions. The location of the meteorological stations used for the study is presented in Figure 2.

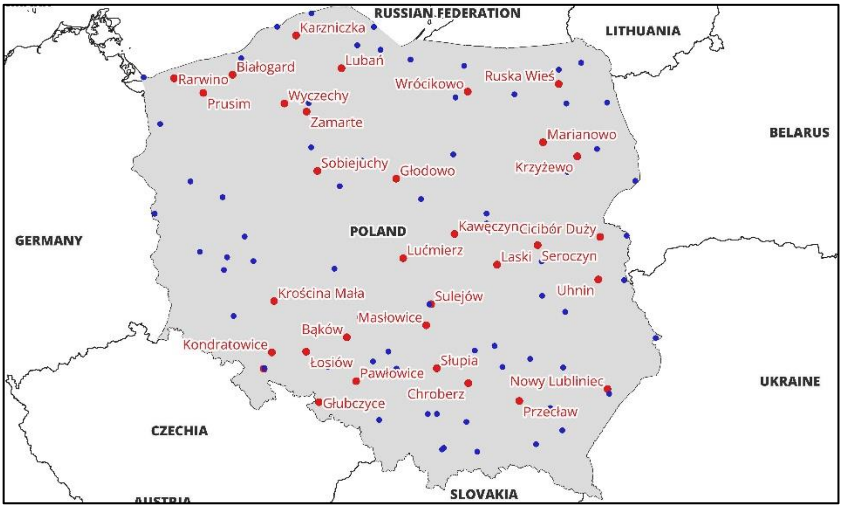

Figure 2. Locations of the meteorological stations of the Institute of Meteorology and Water Management (blue dots) and locations of the rye experiments (red dots with labels) which took place between 2014 and 2022 in Poland.

The weather variables used for the analyses were mean annual temperatures and the annual sum of precipitation. The means of temperature and precipitation for all meteorological stations, presented in Figure 2, are shown in Figure 3. The total precipitation was stable over the long-term period, while the mean annual temperature increased in average of 0.06°C per year based on the regression equations, where the year was treated as an independent variable. Independent meteorological variables for the whole year, in the case of FAOSTAT yield data, were for the period January-December (because various crops were used, winter and spring ones). For winter rye from experiments, the September-August period, which is the period of winter rye cultivation, was used.

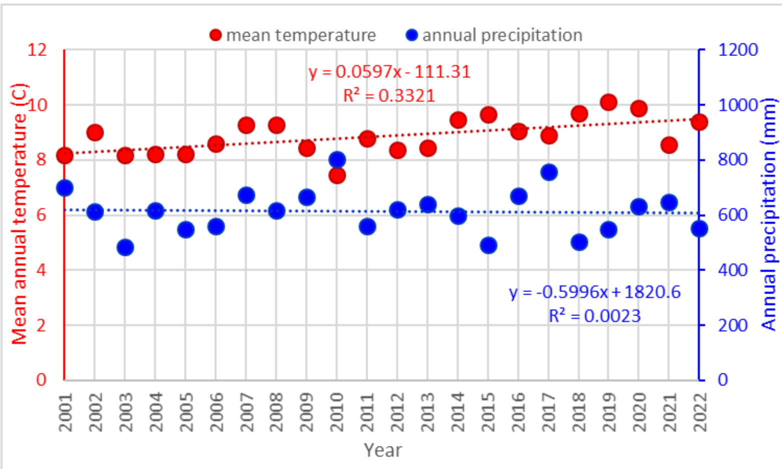

Figure 3. Mean annual temperatures and an annual sum of precipitation between 2014 and 2022 in Poland based on the data from meteorological stations of the Institute of Meteorology and Water Management which are presented in Figure 2.

The study utilized the data from the Polish Research Centre for Cultivar Testing (COBORU 2023) to evaluate the yield of the high-yielding winter rye cultivar “Antonińskie” in multi-environmental trials. COBORU's main focus is the testing and evaluation of new crop cultivars. It conducts cultivar testing and registration trials, as well as research on plant breeding, genetics, and other related fields. The organization's primary mission is to provide reliable and comprehensive information on the performance of new cultivars under different environmental conditions, with the aim of promoting the development and adoption of high-quality, high-yielding crop cultivars in Poland.

The data includes observations from 32 field trial locations across Poland over nine growing seasons, from 2013/2014 to 2021/2022. The study considered two agronomical intensities: moderate (a1) and high input intensity (a2). The moderate input intensity included mineral fertilization, seed preparation, and herbicide and insecticide use. The high input intensity included additional nitrogen fertilization, foliar fertilization, fungicides, and growth regulators. Winter rye was cultivated following standard recommendations for winter wheat production.

The trends of crop yields were evaluated using an analysis of correlation and analysis of linear regression. Analysis was performed with STATISTICA software ver. 13 (STATISTICA 2023). The significance level for all the analyses was set at 0.05.

3. Results

An analysis of the correlation between meteorological variables with crop yields for selected crops was performed to evaluate the effect of weather conditions on yield variability. The results showed a positive correlation between the sum of precipitation and crop yield (Table 1). We observed relatively stronger correlations between the sum of precipitation and annual precipitation with the grain yield of cereals. The correlations between the sum of precipitation with the yield of potato and sugar beet were much weaker but still positive. Most of the correlations between mean temperatures with cereal crop yields were negative while with the yield of potato and sugar beet, the correlations were positive in the case of the mean temperature for the April-June period and for the mean annual temperature. The correlations were relatively stronger between crop yields with precipitation in comparison to the correlations with mean temperature. Selected relationships between weather variables and crop yield were presented using scatterplots. Linear regressions were applied to evaluate the relationships. Figure 4 presents the relatively stronger relationships for the sum of precipitation for the April-June period. The regression lines are almost parallel and the coefficients of all regressions are very similar, i.e. near to 0.004. It means that an increase in precipitation by 100 mm in the April-June period increases the grain yield of cereals by an average of 0.4 t/ha. Figure 5 presents the relationships between the sum of annual precipitation and crop yields of selected cereals, for which the relationships were relatively stronger. The regression lines are similar for oat and barley, while for maize regression coefficient is greater. The increase in grain yield caused by the increase in annual precipitation is much bigger in the case of maize (0.5 t/ha per each 100 mm increase of annual precipitation) in comparison to other cereals (0.15-0.17 t/ha per 100 mm increase of annual precipitation). The highest sums of annual precipitation are probably not very positive, because above 800 mm of annual precipitation (in 2010) grain yield was moderate. The effect of precipitation and temperature is usually opposite because if the precipitation is high temperature is usually low.

Table 1. Correlation coefficients between crop yield (t/ha) of selected crops in Poland with meteorological variables for years 2006-2019.

	Barley	Maize	Oats	Potatoes	Rye	Sugar beet	Wheat
Sum of precipitation, April-June	0.44	0.31	0.48	-0.03	0.45	-0.10	0.32
Sum of annual precipitation	0.40	0.46	0.43	0.17	0.35	-0.09	0.31
Mean temperature, April-June	-0.25	0.16	-0.27	0.24	-0.30	0.23	-0.24
Mean annual temperature	-0.03	-0.21	-0.13	0.20	-0.01	0.26	-0.10

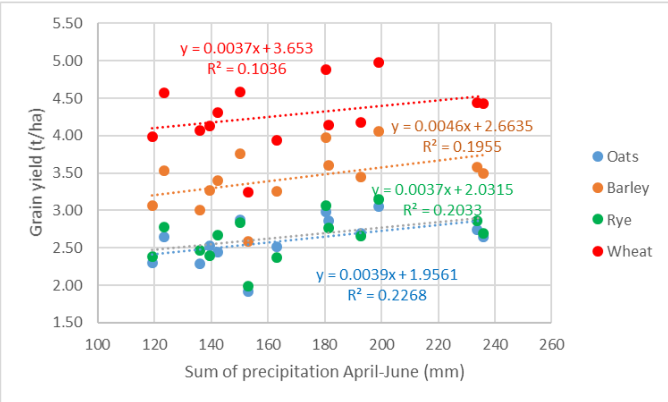

Figure 4. Relationship between the sum of precipitation for the April-June period and grain yield of selected cereals for the whole of Poland based on the data between 2006-2019.

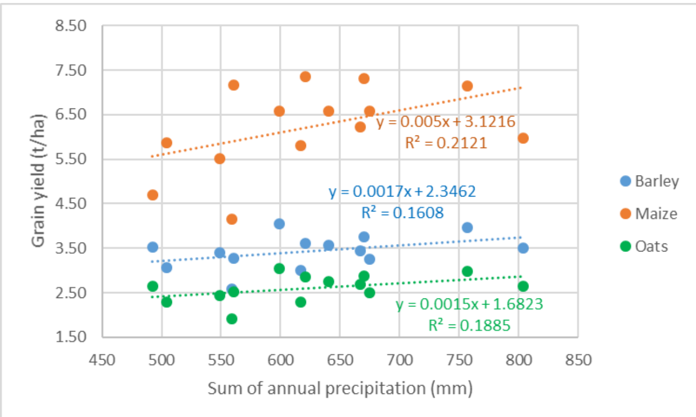

Figure 5. Relationship between the sum of annual precipitation and grain yield of selected cereals for the whole of Poland based on the data between 2006-2019.

The grain yields of winter rye cv. Antonińskie in experiments across Poland in different years are presented in Table 2. The relationship between mean temperature for the April-June period and grain yield of winter rye cv. Antonińskie for years 2014-2022 for all locations with experiments is presented in Figure 6. The yields ranged from about 3 t/h to about 11.5 t/ha. The yields were on average about 2-3 higher in comparison to grain yields in farms all over Poland. Grain yield at high input crop management (a_2) was higher by 13-20%, depending on the year, in comparison to moderate input crop management (a_1). The differences between the means for different years were relatively small, the range of yields was 1.1 t/ha for a_1 and 1.4 t/ha for a_2. The differences were similar to those obtained for the means of crop yield of winter rye for farms in Poland (1.2 t/ha), but the yields were much lower, and the relative variability between years was much higher.

Table 2. Mean, Min, Max, and SD of winter rye yield cv. Antonińskie in experiments in the subsequent years used in the study.

	Yield [10^{-1} t/ha]			
Year	Mean	Min	Max	SD
		a_1		
2022	72.8	33.2	98.8	13.9
2021	67.9	45.9	88.8	12.3
2020	69.1	44.0	95.7	10.7
2019	63.7	45.2	89.0	10.5
2018	62.0	28.3	97.0	14.0
2017	71.1	38.6	96.5	14.4
2016	66.3	32.1	86.6	13.3
2014	69.9	37.2	103.3	15.6
2015	73.2	37.9	101.9	15.6
		a_2		
2022	82.5	30.8	105.9	16.0
2021	78.5	50.7	108.7	14.1
2020	82.2	55.5	105.0	11.6
2019	74.5	49.7	98.0	13.3
2018	70.8	32.9	109.6	14.7
2017	85.2	52.8	113.8	15.7
2016	77.3	34.8	93.3	12.9
2014	82.3	48.0	108.8	15.3
2015	84.5	52.0	114.6	15.6

The experiments were conducted in 32 locations across Poland, in different soil and weather conditions. Therefore, the analysis of correlation was performed separately for each location. The correlation coefficients are presented in Table 3. The results are not consistent and in many cases quite different (positive or negative) for various locations. The most consistent correlations for almost all locations were observed between mean temperature in the April-June period with grain yield of winter rye. Most of the correlations were negative and only some of them were positive. It means that the higher the temperature in the April-June period, the lower the grain yield. The strongest negative correlations were observed in Karżniczka and Wyczechy, i.e. locations in the north of

Poland. The relationship between the mean temperature for the April-June period and the grain yield of winter rye for all locations with experiments is presented in Figure 3. The regression equations for a_1 and a_2 have similar slopes. An increase in the mean temperature by 1℃ is associated with a decrease in the grain yield of winter rye by about 0.3 t/ha. Temperature is usually negatively correlated with precipitation, therefore most of the correlations between the sum of precipitation for the April-June period with grain yield are positive.

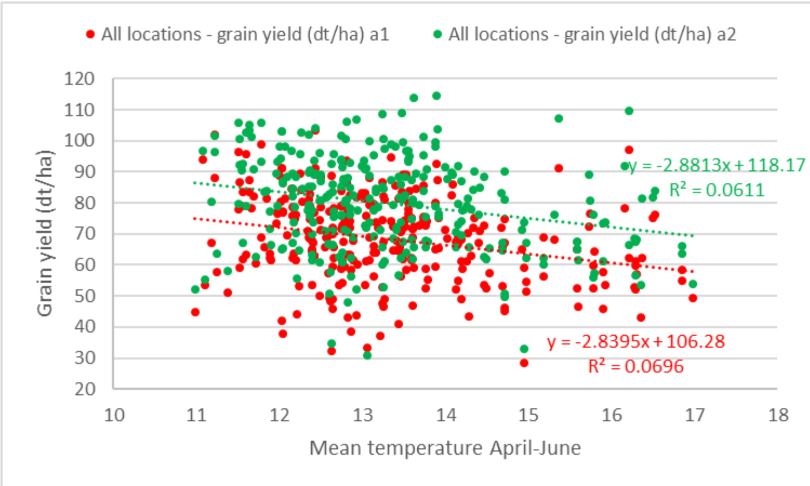

Figure 6. Relationship between mean temperature for the April-June period and grain yield of winter rye cv. Antonińskie for years 2014-2022 for all locations with experiments.

Table 3. Correlation coefficients between crop yield (t/ha) of winter rye in various locations and different input intensities (a_1- moderate; a_2 - high) with meteorological variables for years 2014-2022 (in red font are presented significant correlations at 0.05 significance level).

	Precipitation April-June		Precipitation October-November		Sum of annual precipitartion		Mean temperature April-June		Mean temperature October-November		Mean annual temperature	
Location	Grain yield a1	Grain yield a2	Grain yield a1	Grain yield a2	Grain yield a1	Grain yield a2	Grain yield a1	Grain yield a2	Grain yield a1	Grain yield a2	Grain yield a1	Grain yield a2
Białogard	0.43	0.14	0.37	0.59	-0.03	0.22	0.16	-0.06	0.03	-0.24	0.03	0.01
Rarwino	-0.40	-0.65	0.29	0.03	-0.20	-0.60	-0.14	0.20	0.50	0.79	0.20	0.78
Prusim	-0.25	0.04	0.25	-0.09	-0.09	0.02	-0.17	-0.47	0.06	-0.05	0.35	0.23
Karżniczka	0.56	0.52	-0.56	-0.64	-0.18	-0.25	-0.74	-0.90	0.10	-0.11	0.03	-0.31
Lubań	-0.18	-0.21	0.47	0.39	0.06	-0.03	0.51	0.45	0.33	0.41	0.19	0.24
Wyczechy	-0.09	0.01	-0.49	-0.49	-0.28	-0.23	-0.69	-0.82	-0.34	-0.22	-0.16	-0.22
Wrócikowo	-0.32	0.03	-0.08	-0.41	-0.58	-0.68	-0.39	-0.18	-0.57	-0.34	-0.66	-0.07
Ruska Wieś	0.79	0.77	-0.41	-0.35	-0.16	-0.23	-0.57	-0.50	-0.11	-0.18	-0.09	-0.04
Marianowo	-0.39	-0.02	0.38	0.04	-0.45	-0.46	-0.37	-0.60	-0.82	-0.50	-0.77	-0.38
Krzyżewo	0.57	0.51	-0.42	-0.53	0.24	0.10	-0.10	-0.23	0.50	0.42	0.39	0.41
Seroczyn	0.04	0.30	-0.81	-0.74	-0.54	-0.61	-0.18	-0.14	0.36	0.39	0.55	0.52
Kawęczyn	0.54	0.55	0.21	0.10	-0.16	-0.29	-0.13	-0.18	-0.56	-0.52	-0.42	-0.26
Laski	0.36	0.15	-0.48	-0.55	-0.16	-0.41	-0.76	-0.69	-0.04	-0.20	-0.15	-0.06
Sobiejuchy	-0.46	-0.27	0.01	-0.24	-0.28	-0.28	-0.35	-0.38	-0.15	-0.34	-0.60	-0.49
Głodowo	0.12	0.32	-0.29	-0.15	-0.55	-0.07	-0.19	-0.23	-0.32	-0.33	0.12	-0.28
Zamarte	0.02	-0.01	-0.18	-0.09	-0.23	-0.11	-0.74	-0.66	0.11	0.26	-0.20	-0.05
Kondratowice	-0.42	-0.46	0.20	0.17	-0.41	-0.37	0.35	0.29	-0.37	-0.20	-0.28	-0.28
Krościna Mała	0.34	-0.18	0.17	0.25	0.38	0.10	-0.75	-0.49	-0.14	-0.23	-0.27	-0.21
Tarnów	0.04	0.21	0.09	0.10	0.07	0.17	-0.53	-0.71	0.17	0.11	0.11	-0.16
Sulejów	-0.32	-0.35	0.28	0.38	-0.41	-0.40	-0.51	-0.42	-0.02	-0.09	-0.48	-0.43
Lućmierz	0.52	0.75	-0.22	-0.12	0.25	0.31	-0.68	-0.60	0.34	0.06	-0.46	-0.43
Masłowice	0.35	0.33	0.03	0.12	0.30	0.27	-0.65	-0.73	0.31	0.10	-0.54	-0.71
Głubczyce	-0.34	-0.35	-0.14	-0.17	-0.05	-0.47	-0.14	-0.31	0.13	-0.32	0.02	-0.26
Bąków	-0.23	-0.08	0.51	0.49	-0.06	0.07	-0.01	-0.13	0.31	0.34	-0.01	-0.11
Łosiów	0.41	0.38	0.36	0.10	0.55	0.58	-0.71	-0.66	-0.12	-0.19	-0.74	-0.72
Pawłowice	-0.15	0.33	0.16	0.05	0.08	0.09	-0.63	-0.74	-0.25	-0.39	-0.53	-0.70
Słupia	-0.54	-0.72	-0.11	0.28	-0.57	-0.31	0.64	0.58	-0.13	-0.31	0.37	-0.05
Chroberz	-0.17	-0.53	-0.53	-0.44	-0.90	-0.86	-0.65	-0.48	0.24	-0.06	-0.03	-0.10
Cicibór Duży	0.10	0.15	0.69	0.60	0.25	0.19	0.00	-0.11	-0.67	-0.63	-0.34	-0.30
Uhnin	0.69	0.58	0.03	0.26	0.48	0.49	-0.36	-0.21	0.34	0.17	0.02	0.07
Przecław	-0.14	0.03	0.07	0.07	0.26	0.32	0.29	0.30	-0.03	0.20	-0.26	-0.07
Nowy Lubliniec	-0.65	-0.26	-0.75	-0.33	-0.66	-0.08	0.14	0.57	-0.14	-0.01	-0.12	0.24

4. Discussion

The results of this study showed a weak or moderate relationship between weather conditions and grain yield. Such results were obtained because the differences between observed weather conditions were not extreme. Extreme drought was not observed, nor were extreme temperatures, which would cause very unfavorable growth conditions. The climate conditions were still at least sufficient for the growth of the crops. Correlation coefficients across locations were varied. Weather conditions can fluctuate significantly from year to year. These variations can influence crop yield differently in different years. Different locations in Poland may have distinct microclimates and soil characteristics, leading to variations in crop performance and responsiveness to meteorological variables. Differences in agricultural practices, such as the use of fertilizers, sowing dates, crop rotations, and crop protection strategies, can affect crop yield and its correlation with meteorological variables.

In the case of the analyses conducted using FAOSTAT data for the whole of Poland, a relatively stronger relationship was observed between precipitation and grain yield than between temperature and grain yield of the studied crops. The correlation between grain yield and precipitation was positive, meaning that higher precipitation is associated with higher grain yield, while the correlation with temperature was negative which means that higher temperature is related to lower yield. The correlation between temperature and precipitation is usually negative, a period with higher precipitation tends to have lower temperature. In the study by Łabędzki and Bąk (2017), a strong relationship between water deficit, which occurs in periods of shortage of precipitation, and crop yields in the condition of Poland was observed. A study by Urban et al. (2022) proved that in recent years the probability of drought conditions is higher, especially in central Poland. Southern and northern Poland is less susceptible to such unfavorable conditions. Despite climate warming, there is a very large spatial and inter-year variability. For example, in 2015 very low precipitation was observed, but in years 2016 and 2017 much higher precipitation occurred in Poland. In the study of Smorowska (2022), the most severe drought sequence was observed in recent years, amplified by exceptionally high air temperature, low precipitation, and a high deficit in the climatic water balance. A certain problem related to climate change is the occurrence of extreme phenomena, including periods of very high temperatures, accompanied by low or no rainfall. This causes a large shortage of water for crops and, consequently, lower yields. An example of such a course of weather was 2019, which in Poland was the year with the highest annual temperature in modern history (Ziernicka-Wojtaszek, 2021). The values of the climatic water balance calculated for the June–August period for Poland were very strongly negative. The most threatened were spring crops. The attempt of the study was also to evaluate the effect of climate warming on crop yields in Poland in the future. Precipitation in Poland is quite stable, but the increase in temperature will cause a water deficit and especially for most cereals cultivated in Poland, the effect of weather conditions in the future will be negative. The one exception can be maize, the area of which is increasing in Poland because the increase in temperature in April-June is positively correlated with its grain yield. Yields of other species, such as potato and sugar beet, are not very sensitive to climate warming and their yields should be stable or even higher in the future. The yield of winter rye as a crop adapted to colder conditions can decrease if the temperature increases in the future. There is hope of developing new cultivars of rye that will be better adapted to the warmer climate. A study by Webber et al. (2015), in which the effect of climate warming on the yield of selected crops in Europe in 2050 forecasts an increase in maize, potato, and sugar beet yields for most of Poland, which is consistent with our results. In this study, the strongest decrease in winter rapeseed yields is forecast. Grain yields of winter wheat and barley will vary depending on the region of Poland and will be probably stable overall in Poland. In the study by Zimmermann, etc. (2017), various effects of climate change were evaluated. An increase in yield of all studied crops is forecast in 2050 when the effect of higher concentrations of CO_2 in the atmosphere, as well as technological progress, are included. The countries of Central and Northern Europe will benefit from a warming climate, while the countries of Southern Europe will reduce crop yields. Technological progress, including genetic improvement of cultivars, allows for increasing yields in Poland despite climate warming (Aggarwal, etc. 2019, Oleksiak, etc. 2022; Huzsvai, etc. 2020).

5. Conclusions

The study aimed at evaluating the effect of climate change on selected crop yields in Poland, particularly from 2006 to 2019 at the scale of total Poland and for winter rye from 2014 to 2022 for selected locations in Poland. The effect of climate change on crop yield was assessed. The study may be relevant and important, given the significant increase in temperature observed in recent years worldwide, including in Poland. Crop production is critical for livestock feeding and food production, making it essential to evaluate the potential impact of climate change on crop yields. Overall, the study may provide valuable insights into the potential effects of climate change on crop production in Poland, which may have important implications for agricultural and food systems in the country. The results of the study proved a relatively stronger effect of precipitation for most of the crops than the effect of temperature. Precipitation was positively correlated with the yields of most crops. Higher precipitation caused higher yields. Temperature was negatively correlated with cereal grain yields but positively correlated with yields of sugar beet and potato. The results, based on winter rye experimental data, showed a negative correlation between temperature for the April-June period and grain yield for most locations. An increase in temperature by 1°C in this period was associated with a decrease in grain yield by 2.9 t/ha. Precipitation in Poland is quite stable, but the increase in temperature will have a negative effect on the water balance in the soil. Weather conditions observed during the period of the study were not extreme and because of that effect of meteorological variables was not very strong in most cases. However, we do not exclude that the weather conditions may be more extreme in the future and have a stronger effect on crop yields.

Acknowledgments: The study was supported by the Warsaw University of Life Sciences within the System of Financial Support for Scientists and Research Teams No. 853-2-80-45-700500-S22004.

References

Aggarwal, P., Vyas, S., Thornton, P., Campbell, B. M., Kropff, M. (2019). *Importance of considering technology growth in impact assessments of climate change on agriculture*. Global Food Security, 23, 41-48.

Blecharczyk, A., Sawinska, Z., Małecka, I., Sparks, T. H., Tryjanowski, P. (2016). *The phenology of winter rye in Poland: an analysis of long-term experimental data*. International Journal of Biometeorology, 60, 1341-1346.

Bushuk, W. (2001). *Rye production and uses worldwide*. Cereal Foods World, 46(2), 70-73.

Chmielewski, F. M., Köhn, W. (2000). *Impact of weather on yield components of winter rye over 30 years*. Agricultural and Forest Meteorology, 102(4), 253-261.

COBORU (Research Centre for Cultivar Testing) https://coboru.gov.pl. Accessed 01/04/2023.

Hadasch, S., Laidig, F., Macholdt, J., Bönecke, E., Piepho, H. P. (2020). *Trends in mean performance and stability of winter wheat and winter rye yields in a long-term series of variety trials*. Field Crops Research, 252, 107792.

Herbstritt, S.; Richard, T.L.; Lence, S.H.; Wu, H.; O'Brien, P.L.; Emmett, B.D.; Kaspar, T.C.; Karlen, D.L.; Kohler, K.; Malone, R.W. *Rye as an Energy Cover Crop: Management, Forage Quality, and Revenue Opportunities for Feed and Bioenergy*. Agriculture 2022, 12, 1691. https://doi.org/10.3390/agriculture12101691

Huzsvai, L., Zsembeli, J., Kovács, E., Juhász, C. (2020). *Can Technological Development Compensate for the Unfavorable Impacts of Climate Change? Conclusions from 50 Years of Maize (Zea mays L.) Production in Hungary*. Atmosphere, 11(12), 1350.

Królczyk, J. B., Latawiec, A. E., Kuboń, M. (2014). *Sustainable agriculture-the potential to increase wheat and rapeseed yields in Poland.* Polish Journal of Environmental Studies, 23(3), 663-672.

Kundzewicz, Z. W., Matczak, P. (2012). *Climate change regional review: Poland.* Wiley Interdisciplinary Reviews: Climate Change, 3(4), 297-311.

Łabędzki, L., Bąk, B. (2017). *Impact of meteorological drought on crop water deficit and crop yield reduction in Polish agriculture.* Journal of Water and Land Development, 34(1), 181-190.

Oleksiak, T., Spyroglou, I., Pacoń, D., Matysik, P., Pernisová, M., Rybka, K. (2022). *Effect of drought on wheat production in Poland between 1961 and 2019*. Crop Science, 62(2), 728-743.

Peltonen-Sainio, P., Jauhiainen, L., Laurila, I. P. (2009). *Cereal yield trends in northern European conditions: Changes in yield potential and its realisation.* Field Crops Research, 110(1), 85-90.

Pińskwar, I., Choryński, A., Kundzewicz, Z. W. (2020). *Severe Drought in the Spring of 2020 in Poland—More of the Same?*. Agronomy, 10(11), 1646.

Shao, X., DiMarco, K., Richard, T.L. et al. (2015) *Winter rye as a bioenergy feedstock: impact of crop maturity on composition, biological solubilization and potential revenue*. Biotechnol Biofuels 8, 35. https://doi.org/10.1186/s13068-015-0225-z

STATISTICA (2014) StatSoft STATISTICA ver. 13 (Data Analysis Software System) 2014; TIBCO Inc.: Palo Alto, CA, USA.

Szwed, M. (2019). *Variability of precipitation in Poland under climate change.* Theoretical and Applied Climatology, 135(3-4), 1003-1015.

Urban, G., Kuchar, L., Kępińska-Kasprzak, M., Łaszyca, E. Z. (2022). *A Climatic water balance variability during the growing season in Poland in the context of modern climate change*. Meteorologische Zeitschrift, 31(5), 349-365.

Webber, H., Zhao, G., Wolf, J., Britz, W., de Vries, W., Gaiser, T., Hoffman, H. Ewert, F. (2015). *Climate change impacts on European crop yields: do we need to consider nitrogen limitation?*. European Journal of Agronomy, 71, 123-134.

Wójcik-Gront, E. (2018). *Variables influencing yield-scaled global warming potential and yield of winter wheat production*. Field Crops Research, 227, 19–29.

Yin, X., Struik, P. C., Kropff, M. J. (2004). *Role of crop physiology in predicting gene-to-phenotype relationships*. Trends in Plant Science, 9(9), 426-432.

Ziernicka-Wojtaszek, A. (2021). *Summer Drought in 2019 on Polish Territory—A Case Study*. Atmosphere, 12(11), 1475.

Zimmermann, A., Webber, H., Zhao, G., Ewert, F., Kros, J., Wolf, J., Brtitz W., de Vries, W. (2017). *Climate change impacts on crop yields, land use and environment in response to crop sowing dates and thermal time requirements*. Agricultural Systems, 157, 81-92.